Dynamics of evaporation of a fast-moving target under impact of high power laser radiation

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Evaporation of a target, moving with a high speed (~50 m/s) under impact of laser radiation has been investigated. The range of laser power density $I = 6\div12 \cdot 10^6$ W/cm^2 has been found, at which the pulse mode of the evaporation appears. It is proved theoretically that the occurrence of a discontinuous trace with smoothly varying periodicity is connected with nonlinear character of radiation interaction with the target substance under impact of thermo-chemical mechanisms, in particular, the process of the burning of metal. The developed technique of simultaneous registration of luminosity of a plasma plume in a wide range of intensity allowed the transformation of the recorded signal to distinctly observed micro-pulsations. Observable pulsations correspond in time to the fragment of the print, where the discontinuous trace with varying periodicity is observed.

Introduction

Today, numerous studies are devoted to interaction of laser radiation with substances.[1] Many problems are related with phenomena appearing under impact of the laser radiation on different media, for example, the processes observed at radiation interaction with non-transparent condensed media, mainly, with metals. The reason of such interest is the application of laser instrumentation to metallurgy, electronics, and other branches of industry.

Attempts to increase the efficiency of lasers in technological processes activated the study of factors affecting the character and results of laser impacts. Among these factors are the following: the material of the target; the intensity, wavelength, and polarization of the light beam; the mode of generation; the composition and pressure of the surrounding medium; the state of the surface, etc. Representation of a full pattern of interaction in this case is difficult and reduced to consideration of individual models describing physical-chemical mechanisms of radiation impacts in particular cases.

In this paper we consider interaction of laser radiation with a metal target, moving with a high speed.

Experiment

The schematic view of the experimental setup is shown in Fig. 1.

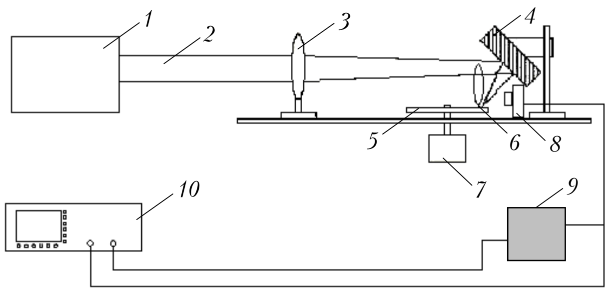

Fig. 1. Schematic view of the laser setup: CO_2 laser (*1*); laser radiation (*2*); focusing KCl lens (*3*); reflecting mirror (*4*); rotating target (steel disk) (*5*); plasma plume (*6*); engine (*7*); PEC-29, SPU-M (*8*); diagram of logarithmic amplifier (*9*); oscillograph (*10*).

Radiation of the laser *2* is focused by KCl lens *3* with the help of the reflecting mirror *4* to the rotating disk *5*, attached to the engine *7*. Under impact of laser radiation on the target, the plasma plume *6* is formed above the target. Brightness of the plume is recorded by the photoelectron camera (PEC-29, SPU-M). The signal from the camera is visualized on display and recorded by the two-channel oscillograph *10*.

The electro-ionization CO_2 laser NEIL-20 served as a radiation source.[2] The choice of this laser was caused by the necessity of operation in the mode of single pulses with preset amplitude and length. The disk of the stainless steel with a diameter of 200 mm, rotated by the engine with a frequency of 10–400 rot/min, was used as the target. The experiments were carried out at the atmospheric pressure and room temperature. The experiment was aiming at revealing the radiation-intensity dependence of the evaporation based on the trace spatial scans.

The interesting pattern of the laser radiation interaction with the target was revealed, disagreeing with all available models (Fig. 2*a*)

A solid trace was observed in the focal spot at the increase of the radiation intensity from 0.8 to $6.0 \cdot 10^6$ W/cm^2. Then, up to $1.7 \cdot 10^6$ W/cm^2, a dot trace appeared, which gave the impression of discontinuous evaporation mode known as the pulsing plasmotrone. However, it was surprising that at further intensity increase the trace again became solid.

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The change of the evaporation modes was observed both at rising and tilting pulses in the aforementioned range of intensities ($6.0 \cdot 10^6 - 1.2 \cdot 10^7$ W/cm^2). At radiation pulse amplitude, not exceeding $7 \cdot 10^6$ W/cm^2, the pulsed evaporation mode was observed during the time corresponding the plane top of the pulse (Fig. 2*b*).

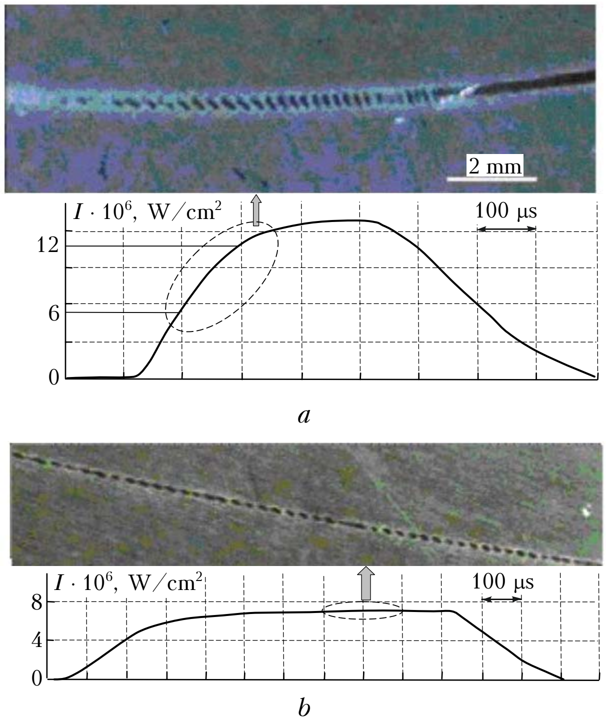

Fig. 2. Photos of different fragments of the radiation trace on the target and corresponding oscillograms of the radiation pulses. The marked parts on the oscillograms correspond to the trace photos.

It should be noted that if the disk was pre-anneal in a stove with raising the scale on its surface, the discontinuous trace was not formed. Thus, the main reason of appearance of the dot trace is the process of burning the target material, which, as is known, can be unstable under some conditions.

Obviously, the instability of the burning is observed in the case, when the thermal energy of oxidation becomes comparable with the laser energy. In this case, the beginning process of burning leads to depletion of oxygen in neighboring areas. If the depleted area is brought into the zone of the laser beam impact, the burning does not occur because of the lack of oxygen. Thus, there appear alternating areas of flashing and relaxing; in the latter area the oxygen is accumulated. It is reasonable to assume that the characteristic sizes of the flashing and relaxing areas are comparable with the diameter of the focusing spot.

At the energy of laser beam, essentially higher than the energy of oxidation, the process of the target evaporation should be stable, because it does not depend on the presence of oxygen in the area of the laser beam impact.

The model

For mathematical description of the laser-induced burning we used the model, which included equations for temperature, concentration of oxygen, and the thickness of the oxide film:

$$\frac{dT}{dt} = \frac{1}{c_v}\left\{P(t) + \frac{k_0(T) n_{O_2} QR}{x} - \frac{1 \cdot 10^5 \exp\left[\frac{-DH1}{8.3}\left(\frac{1}{T} - \frac{1}{T_{k1}}\right)\right]}{kT} \times v(T, ma1)\frac{DH1}{N_A} - \lambda \frac{(T-300)}{5 \cdot 10^{-6}}\right\}, \quad (1)$$

$$\frac{dn_{O_2}}{dt} = -\frac{k_0(T)\rho 1 n_{O_2}}{ma1 x r} + D(T)\frac{(9 \cdot 10^{24} - n_{O_2})}{r^2}, \quad (2)$$

$$\frac{dx}{dt} = \frac{k_0(T) n_{O_2}}{x} - \frac{1 \cdot 10^5 \exp\left[\frac{-DH1}{8.3}\left(\frac{1}{T} - \frac{1}{T_{k1}}\right)\right]}{kT} \times v(T, ma1)\frac{ma1}{\rho 1}, \quad (3)$$

where T is the target temperature; c_v is the thermal capacity; $P(t)$ is the power density of radiation; $k_0(T)$ is the reaction constant; n_{O_2} is the oxygen concentration; QR is the specific heat of burning; $DH1$ is the specific heat of the oxide evaporation; v is the thermal velocity of molecules; λ is the thermal conductivity; $ma1$ is the oxide atom mass; $\rho 1$ is the oxide density; x is the oxide film thickness; r is the focal spot radius; $D(T)$ is the diffusion coefficient; T_{k1} is the oxide evaporation temperature.

The physical values and constants, necessary for calculations, were borrowed from Refs. 3 and 4.

To simplify the model, the constant spatial distribution of the laser radiation intensity in the focal spot, moving relative to the disk, was replaced with equivalent immobile one, but changing in time $P(t)$.

The calculations have shown that the regime of oxidation, accompanied by the increase of the oxide film thickness, is followed by the regime of burning (Fig. 3). Then, as the temperature increases, the rate of oxide evaporation increases as well. This leads to decrease of the film thickness up to zero, thus opening the metal surface and initiating the process of burning.

At small intensities of the laser radiation, the time of total evaporation of the oxide film is greater than the time of the laser radiation impact on the fragment of the target. In this case, there occurs a stable oxidation, what corresponds to the continuous fragment in the beginning of the trace.

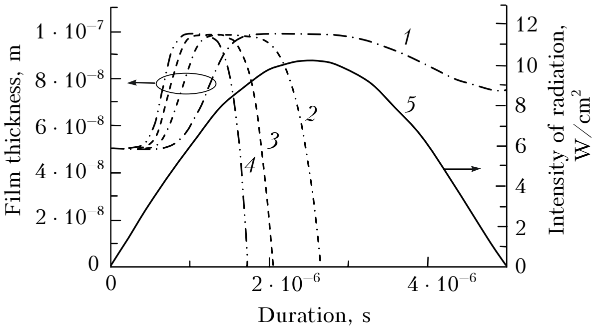

Fig. 3. Change of the thickness of oxide film during the process of the target motion at different intensities of laser radiation: $2.5 \cdot 10^6$ W/cm² (*1*); $5 \cdot 10^6$ W/cm² (*2*); $7.5 \cdot 10^6$ W/cm² (*3*); 10^7 W/cm² (*4*). Solid line (*5*) shows the shape of the laser pulse $P(t)$.

The situation, when approximately at the middle of the pulse (i.e., in the zone of maximal impact on the target) the thickness of the oxide layer becomes zero, corresponds to the area of instable burning (at intensities within the range $6.0 \cdot 10^6 - 1.2 \cdot 10^7$ W/cm²). Under these conditions, the system of equations (1)–(3) takes the form:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{1}{c_v} \times$$

$$\times \left[P(t) + \frac{k_0(T) n_{O_2} (QR - DH1)}{4 \cdot 10^{-10}} - \right.$$

$$- \frac{1 \cdot 10^5 \exp\left[\frac{-DH}{8.3} \left(\frac{1}{T} - \frac{1}{T_k} \right) \right]}{kT} v(T, ma) \times$$

$$\left. \times \frac{DH}{N_A} - \lambda \frac{(T - 300)}{5 \cdot 10^{-6}} \right],$$

$$\frac{\mathrm{d}n_{O_2}}{\mathrm{d}t} = -\frac{k_0(T) \rho 1 n_{O_2}}{ma1 \cdot 4 \cdot 10^{-10} r} + D(T) \frac{(9 \cdot 10^{24} - n_{O_2})}{r^2},$$

where DH is the specific heat of evaporation of iron; ma is the iron atom mass; ρ is the iron density; T_k is the iron evaporation temperature.

The obtained solutions are characterized by minimal resistance to the change of both initial and boundary conditions. The appearance of instable solutions well corresponds to the qualitative interpretation as instable mode of burning.

If the intensity of radiation is sufficiently high, then the time of total evaporation of the oxide film is much less than the time of the laser pulse impact, i.e., there appears the stable burning, which also forms the continuous trace on the target.

Recording of plume luminosity

Results of above calculations give the following pattern of the laser plume luminosity. At the beginning of the pulse, in the stable oxidation mode, the plume luminosity is very weak or not observed at all. Then the plume luminosity mode becomes pulsing, that corresponds to the segment of instable burning. Continuous and quite intensive luminosity of the plume corresponds to the next segment of stable burning.

The purpose of the experiment was to record variations of the luminosity of the plasma plume during the whole period of the radiation pulse impact and then to compare the oscillograms of the plume luminosity with the patterns of traces on the target surface.

The plasma plume was observed in the series of experiments, which had a wide range of luminosity intensity and appeared above the target surface due to impacts of the laser radiation.

The PEC-29 SPU-M was used as the recording device. The level of the direct signal from PEC was detected at the input resistor $R_1 = 1$ kΩ.

Figure 4 shows the image of the trace fragment (*a*) and the corresponding fragment of the oscillogram (*b*), which distinctly demonstrates the pulsing character of the metal target burning.

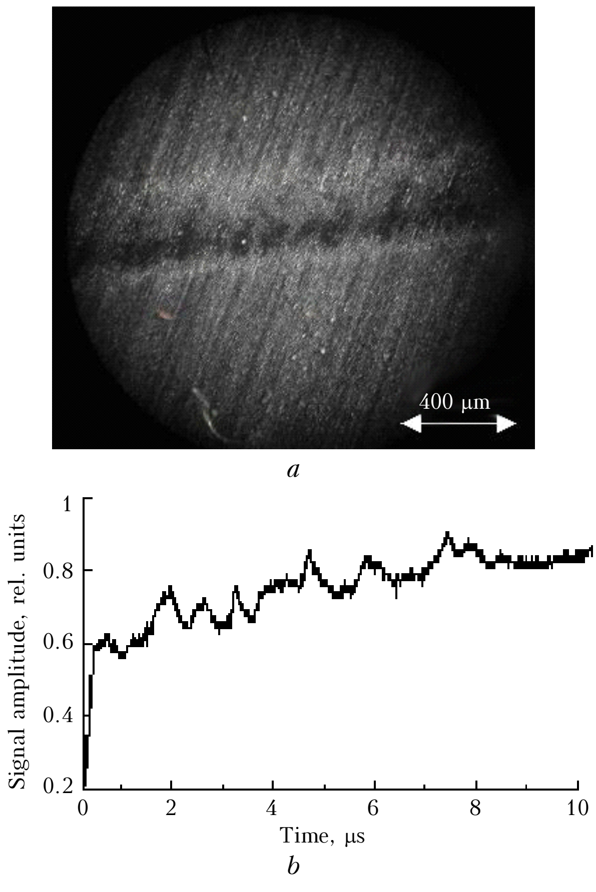

Fig. 4. Fragment of the trace on the target surface (*a*) and the corresponding oscillogram, recorded by PEC characterizing the plume luminosity (*b*).

Signal pulsations on the oscillogram, recorded at the output of PEC coincide with the dot trace on the target. Then the intensity of the plasma plume luminosity becomes monotonous, that corresponds to the stable burning mode and to continuous trace on the target.

It is seen that, when reaching a certain power density, the oscillating component is added to the increasing intensity of the plume luminosity, which reflects the influence of the effect of the burning of the metal target under the laser radiation impact.

Conclusions

Thus, the relation of the pulsing mode of evaporation with the burning of the metal target inside oxidizing medium under the impact of laser radiation is shown experimentally and theoretically. However, it should be mentioned that we conducted only preliminary theoretical investigation of the above-described process, using the estimating model. The theoretical study of the problem in more detail will be the subject of our further investigations.

References

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